Scaled Wind Farm Technology Facility Overview

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In the past decade wind energy installations have increased exponentially driven by reducing cost from technology innovation and favorable governmental policy. Modern wind turbines are highly efficient, capturing close to the theoretical limit of energy available in the rotor diameter. Therefore, to continue to reduce the cost of wind energy through technology innovation a broadening of scope from individual wind turbines to the complex interaction within a wind farm is needed. Some estimates show that 10 - 40% of wind energy is lost within a wind farm due to underperformance and turbine-turbine interaction. The US Department of Energy has recently announced an initiative to reshape the national research focus around this priority. DOE, in recognizing a testing facility gap, has commissioned Sandia National Laboratories with the design, construction and operation of a facility to perform research in turbine-turbine interaction and wind plant underperformance. Completed in 2013, the DOE/SNL Scaled Wind Farm Technology Facility has been constructed to perform early-stage high-risk cost-efficient testing and development in the areas of turbine-turbine interaction, wind plant underperformance, wind plant control, advanced rotors, and fundamental studies in aero-elasticity, aero-acoustics and aerodynamics. This paper will cover unique aspects of the construction of the facility to support these objectives, testing performed to create a validated model, and an overview of research projects that will use the facility.

Nomenclature

BSDS	=	Blade System Design Study
Cp	=	Coefficient of Power
Ct	=	Coefficient of Thrust
CX	=	Carbon Experimental Rotor Blade Design
DOE	=	Department of Energy
DGV	=	Doppler Global Velocimetry
DWM	=	Dynamic Wake Meandering Model
LES	=	Large Eddy Simulation
NASA	=	National Aeronautics and Space Administration
NFAC	=	National full-scale aerodynamic complex
NWI	=	Texas Tech University National Wind Institute
SNL	=	Sandia National Laboratories
SWiFT	=	Scaled Wind Farm Technology Facility
TX	=	Twist-Bend Coupled Rotor Blade

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I. Introduction

IN the past decade wind energy installation has increased exponentially driven by reducing cost from technology innovation and favorable government policy. In recent years wind energy has either led or been second to natural gas in terms of total annual power installation in the US. Modern wind turbines are highly efficient, capturing close to the theoretical limit of energy available in the rotor diameter. Therefore, to continue to reduce the cost of wind energy through technology innovation, a broadening of scope from individual wind turbines to the complex interaction within a wind farm is needed.

To support future wind farm research and development, the Scaled Wind Farm Technology Facility (SWiFT) was developed by the US Department of Energy's Wind Energy Program (DOE) and Sandia National Laboratories (SNL). Additionally, SWiFT was built to test advanced rotors and perform fundamental studies into aero-elasticity, aero-acoustics and aerodynamics. In the following sections, previous work, an overview of the facility, a comparison between experimental and simulation requirements, and a discussion about future work will be presented.

II. Scaled Wind Farm Testing Previous Work

In this section, previous efforts at both scaled and full-scale wind farm experiments will be presented. Of note is the wide range in scales covered in previous work and the lack of a consistent unifying method for scaling the results.

A. Scaled Wind Energy Testing

Within this paper, scaled testing is assumed to be experiments that occur at a size smaller than the typical production wind turbine at the time that the work was performed. Well-planned scaled testing provides numerous benefits, such as, an ability to control the environment / inflow, ease of adding and maintaining instrumentation, high experimental cost-efficiency and the ability to scale results up to current and future sizes. A summary of the scaled tests discussed is presented in Table 1.

One of the most significant scaled research efforts was the NREL Unsteady Aerodynamics Experiments. The Phase II through V experiments were performed in the field on a 2-bladed wind turbine configuration in upwind and downwind campaigns. Much uncertainty was found in the data due to the complexities of field testing. Therefore, in the Phase VI experiment, the test article was placed in the large 80 ft. by 120 ft. NASA Ames wind tunnel to remove the uncertainty. Numerous analyses have been and continue to be performed on the results of this experiment. The challenges of this experiment were that the rotor was 2-bladed instead of the common 3-bladed, the blades were not as flexible as current machines, and with only one machine under test, studies of turbine to turbine interaction could not be performed.

In 2006 to 2012, the Mexnext project analyzed aerodynamic performance data from the EU Mexico test campaign. The test was comprised of a single three-bladed turbine built with ridged blades and mounted in the 9.5 meter by 9.5 meter German Dutch Wind Tunnel (DNW). This test was unique in that the rotor represented the solidity and airfoil types used on modern utility scale machines. The airfoil sections were tested as well for direct comparison to the 3D blade loads, which were acquired using high sample rate surface pressure measurements. Additionally, blade loads were measured and detailed PIV images were taken in the vicinity of the wake-edge vorticity.

At Risø National Laboratory, there is a Vestas V27 turbine installed that has been used on several experimental campaigns. The turbine is three bladed 27 m rotor, fixed speed, and variable pitch with a hub height of 31.5 m as it was delivered from Vestas. Two experimental campaigns of note are the Active Trailing Edge Flaps (ATEF) and nacelle mounted LiDAR experiments. In the ATEF project, the rotor was replaced with a rotor with flaps integrated into the blades to test the ability to actively control lift at a relevant Reynolds number during operation conditions. In the LiDAR experiments, the LiDAR equipment was mounted on the turbine and used to measure wind speeds. The facility also has a Tellus turbine with a 19 m rotor and 29 m hub height. This turbine has been used in rear facing nacelle mounted LiDAR for the scanning of wake deficits.

Sandia National Laboratories performed scaled testing to demonstrate the use of several innovative concepts that are currently used in production wind turbine blades. The Carbon Experimental (CX) blade was used to demonstrate that utilization of carbon composite, although relatively expensive, in strategic locations would produce a more robust and relatively cost-neutral rotor blade. The Twist-bend Experimental (TX) blade was then produced to demonstrate that intelligent placement of off-axis carbon could result in a blade that could passively twist and pitch when under load. The conclusion of this project was a significant reduction in Damage Equivalent Loading for passive load control that could ultimately lead to either larger rotor blades, reduced drivetrain imbalance and/or reduced pitching demand. The Blade System Design Study (BSDS) showed innovative concepts at the time of design, including a large diameter root and the utilization of flatback airfoils. Both of these innovations allowed for more structurally efficient airfoils which led to an overall decrease in rotor blade weight (and cost), increase in blade fatigue life and an unexpected improvement in airfoil performance in soiled conditions. Following these passive load control designs, Sandia initiated a series of active load control rotor blade designs using a building-block approach. The Sensor Blade, Sensored Rotor and SMART Rotor projects iteratively developed a robust sensing system and then a demonstrative load control device that showed the tremendous future opportunity for active load control. The capstone of the series was the flight of the SMART Rotor which was comprised of three active flaps on each rotor blade and full structural and aerodynamic sensing on each blade.

At Politecnico de Milano, a wind turbine experimental testing facility has been developed in partnership with Vestas Wind System A/S. The facility utilizes the existing boundary layer wind tunnel with a cross-section of 13.8m x 3.8 m. A turbine with a 2m rotor has been created based on scaled parameters from a Vestas V90 turbine. The turbine is variable speed and pitch regulated to replicate the degrees of freedom in MW turbines. There are two turbines, allowing controlled wake performance to be studied. The ability to control the inflow to the rotor and the precision scaling and calibration of the turbine create a unique test bed for aeroelastic and wake studies.

Table 1. Previous scaled turbine tests.

	Year	Diameter (m)	Important Data Sets	References
UAE Phase V (Field)	1998	10	Inflow, Surface pressure, loads	[1]
UAE Phase VI (Ames Tunnel)	2000	10	Surface pressure, Dynamic Stall	[2]
Risoe V27 Tests (Field)		27	Active Load Control, Nacelle based wind measurements	[3-5]
Sandia - CX, TX, Sensor, Smart (Field)	2006	18	Spanwise Strain, Flatback airfoils	[6-9]
MEXICO (Tunnel)	2006 - 12	4.5	Unsteady Surface Pressure, Wake PIV	[10, 11]
Bottasso – Vestas (Tunnel, scaled from MW)	2010	2	Wake propagation, Waked turbine performance	[12]

B. Wind Farm Experimental Campaigns

Wind farm field experiments have primarily focused on wind farm performance and turbine-turbine interaction. Following the definition in [13], turbine-turbine interaction tests focus on the detailed interaction of a few turbines, while full-scale wind farm performance tests focus on the power production and wake induced fatigue loads of production machines in a wind farm. Using full-scale production machines offers the advantage of not requiring any special scaling effort, but modern production machines are significantly more expensive than scaled machines, are difficult to access, and typically have limited available data. By focusing on a few turbines, turbine-turbine interaction tests typically offer more robust data sets and are much more accessible to researchers. Table 2 is a summary of previous field test campaigns of turbine-turbine interaction and full-scale wind farms.

Table 2. Previous field test campaigns of turbine-turbine interaction and full-scale wind farms. Modified from [13].

Location	# Turbines	Turbine Type	Turbine Spacing	Instrumentation
Turbine-Turbine Interaction Experiments				
Nibe, Denmark	2	630 kW	5D	4 met masts, blade bending moments
Alsvik, Sweden	4	180 kW Danwin	5D, 7D, and 9.5D$	met masts, blade and tower loads
Ris*o* Test Station, Denmark	2	250 kW Nordex and 225 kW Vestas V27	2D	blade loads
Kegn*ae* s Ende, Denmark	2	450 kW Bonus	2.5D	blade, nacelle, tower loads
Tj*ae* reborg wind farm, Denmark	5	2 MW Nordtec-Micon NM80	3.3D	blade loads, 5-hole pitot tube
ECN WT Test Site Wieringermeer, The Netherlands	5	2.5 MW	3.8D	met mast, turbine data, blade and tower loads
ECN Scale Wind Farm, The Netherlands	10	10 kW Aircon	?	14 met v
Full Scale Wind Farm Experiments				
Norrekaer Enge II wind farm, Denmark	42	300 kW Nordtank	6D-8D	2 met masts, blade loads
Vindeby offshore wind farm, Denmark	11	450 kW Bonus	8.6D	blade and tower loads, 3 met masts, sodar
Bockstigen offshore wind farm, Sweden	5	550 kW Wind World	8.8D-20.9D	one met mast
Middlegrunden offshore wind farm, Denmark	20	2 MW Bonus	2.4 D	one met mast, SCADA data
Horns Rev offshore wind farm, Denmark	80	2 MW Vestas V80	7D	three met masts, SCADA data
Nysted offshore wind farm, Denmark	72	2.3 MW Bonus	10.5D, 5.8D	four met masts, SCADA data
Purdue/GE wind energy park, Indiana, U.S.A.	60	1.5 MW GE	--	--
Lillgrund, Sweden	48	2.3 MW Siemens	3.3D, 4.4D	met mast, SCADA data

III. The DOE/SNL Scaled Wind Farm Technology Facility

In this section, a description of the key aspects of the SWiFT Facility will be presented. Additionally, efforts made to produce an accurate structural elastic model using a building-block experimental approach will be presented.

A. Overview of Scaled Wind Farm Technology Facility

In this section, the important design aspects of SWiFT will be described.

1. Purpose of Facility

The SWiFT facility was designed and established for research and development to support the DOE Wind Energy Program, as well as, private and public sector organizations, such as, universities, companies and other national laboratories. A partnership between DOE, SNL, Vestas Wind Systems, Texas Tech University's National Wind Institute (NWI) and Group NIRE made the development of the SWiFT Facility possible. The principle objectives of SWiFT are:

- Reduce wind plant underperformance and operations & maintenance costs caused by the interaction amongst wind turbines
- Increase energy capture, reduce imbalance loading and decrease wake losses with advanced rotor designs
- Drive future innovation by improving knowledge of aerodynamic, aero-elastic and aero-acoustic phenomenon and simulation
- Provide a public and completely open-source research testbed to support the broader wind energy community

The first phase of the SWiFT Facility, as shown in Figure 1, is comprised of three heavily modified Vestas V27 wind turbines which are intended to replicate the performance and behavior of much larger megawatt scale turbines. The purpose of scaled testing is to replicate megawatt turbines, but decrease complexity of experiments, increase the ability to instrument, reduce testing time and cost, and allow for minimal restrictions on intellectual property. In the current level of market competition, it is inconceivable that the intellectual property of a production wind turbine would be made publically available. Furthermore, with the dramatic rate at which new products and innovations are coming to market any machine would become a scaled testing facility within the time required to develop and install. For these reasons, SNL determined that developing the means and methods for scaled testing was absolutely required and prudent to meet DOE research and development goals.

The Vestas V27 wind turbine was selected for the SWiFT facility because of its high reliability / robust design, a collective pitch system, the ability to convert to variable speed control, a Reynolds number of two-million, and a maximum tip speed of 80 meters per second which will enable direct scaling for comparison to larger production turbines. Although initially comprised of three turbines and two anemometer towers, the ultimate goal is to install an additional seven wind turbines. The goal of adding turbines is to increase the complexity of the facility synchronously with the improvement in the accuracy of wind farm simulations.

Figure 1. Scaled Wind Farm Technology Facility concept (left) and completed construction (right).

2. Location and Layout of Facility

To provide a US facility representative of typical wind farm installations and high-wind-resource, SWiFT was located in Lubbock, TX as shown in Figure 1. The location is at the southern end of the US wind corridor which provides favorable weather conditions all year. A wind resource assessment performed at the site resulted in an average wind speed of 7.5 meters-per-second, a primary wind direction of south, a low-wind (15% below average) season in July and August and a high-wind (15% above-average) season in March and April.

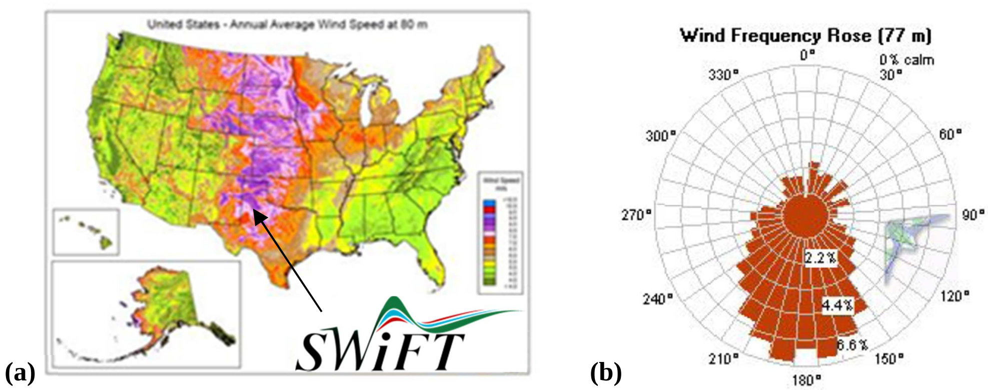


Figure 2. (a) US Wind Resource map showing location of SWiFT Facility and (b) wind frequency rose.

As stated previously, the initial deployment at SWiFT is comprised of three turbines and two anemometer towers as shown in Figure 3. The three turbines were placed in a triangular arrangement of three-, five- and six-diameter spacing. The five-diameter spacing was aligned with True North. The spacing was selected to provide two distinct wake distances to study, dependent on a South or Southwest wind direction without the need to move turbines. Simultaneously, this arrangement provides one wake that is unperturbed in either situation. Farther spacing was not used as it was desirable to be certain to study the turbine-wake interaction and additional aspects covered in [13]. The lateral three-diameter spacing was selected to minimize the statistical variation in testing a control and test rotor in parallel. The goal of this was to improve the standard uncertainty in testing rotors in series on the same machine. In addition to the turbine locations, two anemometer towers were installed 2.5 diameters upwind of the leading wind turbines. Significant effort was made throughout construction to position and orient all turbines within tight tolerances. For example, the overall tower height is within 1”, the elevation of all tower foundations are within 1”, a special installation procedure was performed to ensure the towers were oriented the same relative to True North, and an accounting was made for the rotor overhang, anemometer tower boom length, and sonic anemometers to ensure that the inflow measurement was performed within 1” of precisely 2.5 diameters upwind of the center of the rotor plane.

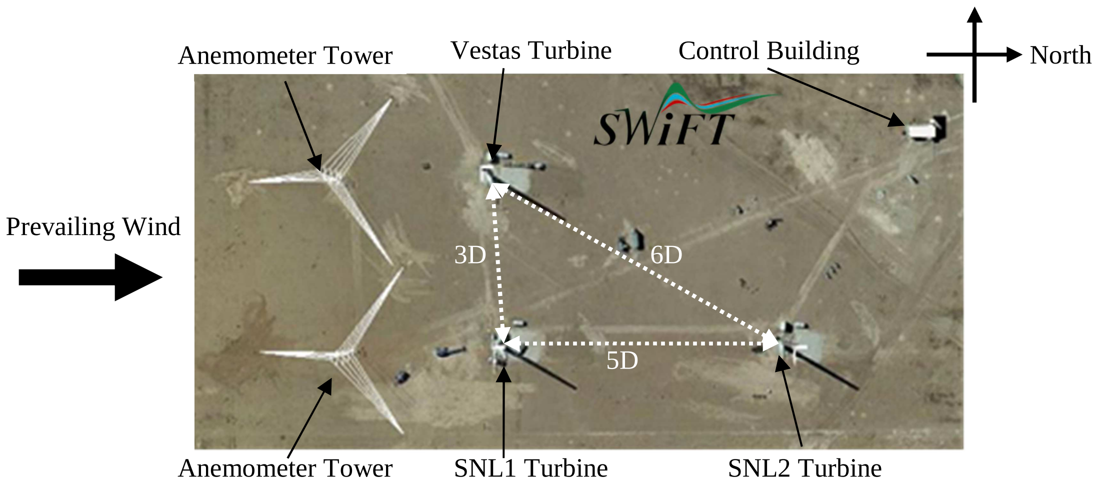


Figure 3. Layout of SWiFT Facility.

3. SWiFT Wind Turbines

As stated previously, the SWiFT wind turbines are heavily modified Vestas V27 225 kilowatt wind turbines. The legacy V27 was the first robust wind turbine produced with collective pitch control and dual fixed-speed operation. The dual fixed-speed operation was created with two sets of windings in the generator that allowed for a lower rpm smaller generator to be contained within a higher rpm larger generator. To provide rotor and wake control more similar to utility-scale wind turbines, the generator was replaced by a modern variable frequency induction generator and power electronics that allowed for full variable speed (Type IV). In doing this the generator was upgraded to 300 kilowatt and the legacy controller was replaced. The new controller utilized the National Instruments CompactRIO hardware and new variable speed software written in Matlab Simulink.

Replacing the controller significantly increased the complexity of the modifications; however, this work resulted in a completely open-source controller that can be reconfigured in the future and the work also expedited the merger of data acquisition and controller. In the current version, the controller and data acquisition are within the same controls environment which allows for synchronous reporting of all data acquired and controls decisions / set points. In the future this controller design will allow for rapid and easy prototyping of new wind turbine and wind plant controls because all data is incorporated and available to the controller from all wind turbines.

Besides the significant investment to upgrading the speed regulation and instrumentation, the basic hardware of the turbine, such as tower, nacelle, blades, yawing components and hydraulics were unchanged so as to retain their dependability. Additionally, significant effort was made to retain and enhance all legacy safety controls to ensure the turbines will be as safe as possible.

4. Inflow Characterization

Detailed characterization of the wind inflow to the turbines is critical to all future research and development efforts. A pair of identical anemometer towers, as shown in Figure 4, was installed 2.5 diameters upwind of the leading row of wind turbines. By aligning a vertical column of three-dimensional sonic anemometers directly upwind (accomplished by shifting the tower to the East) of the turbines, the towers prioritize scientific characterization of the inflow over industrial certification. The industrial certification is accomplished by a set of traditional cup anemometers to the East of the tower. With respect to

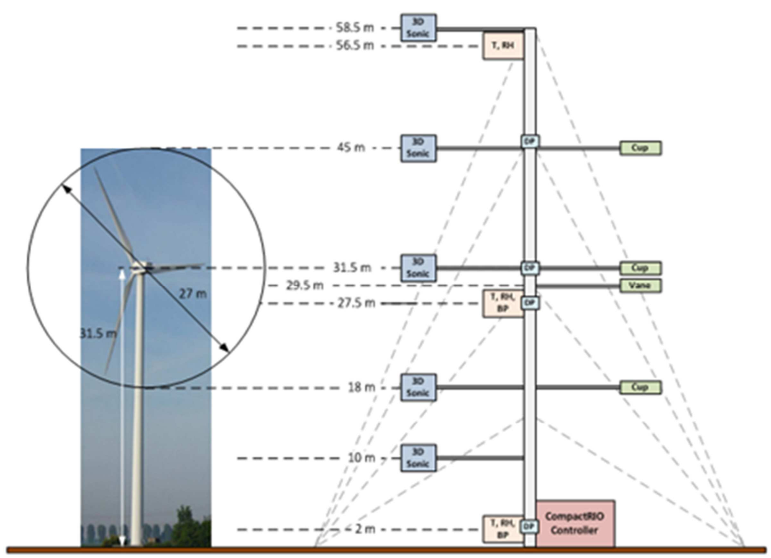


Figure 4. Anemometer tower configuration.

vertical distribution, there are sonic anemometers at: 10 meters from the ground, bottom of the rotor (18 meter), hub-height (31.5 meter), top of rotor (45 meter) and a blade length above the rotor (58.5 meter). Cup anemometers are located at the bottom of the rotor, hub-height and top of rotor. A wind vane is located 2 meters below hub-height. To characterize the environmental conditions and atmospheric conditions, temperature, relative humidity and barometric pressure is measured at the bottom of the tower, hub-height and the top of the tower (no pressure at this location). All data from the tower is synchronized amongst itself and with the overall site using GPS time synchronization.

5. Time-Synchronize Site-Wide Control and Data-Acquisition Network

An important capability of the SWiFT Facility is the site-wide control and data-acquisition network that ensures all sensors and actuators are acquired and controlled synchronously. To accomplish this, the site depends on GPS modules embedded in every controller / data acquisition system (at SWiFT these are the same device) that are able to update and control the device clock which controls the precise instant in time at which a sample is acquired and a command is written out. By controlling the clocks locally with a unifying GPS signal, site-wide devices that communicate via non-deterministic TCP/IP protocol are able to precisely coordinate.

Within a device, such as a wind turbine or anemometer tower, all instrumentation and hardware are synchronized via EtherCAT, a deterministic Ethernet based synchronization protocol. The EtherCAT protocol allows for synchronized devices to be spread over a variety of locations wired in series. For example, the EtherCAT loop in a wind turbine has a central host in the nacelle which is then connected in series to: (1) auxiliary chassis in the nacelle, (2) bottom controller in the base of the tower, (3) ABB variable speed drive adjacent the base of the tower and (4) auxiliary chasses in the rotor hub.

Communications and power in the hub is provided via a custom slip ring on the low-speed shaft. All other communications is sent via single-mode fiber optic cable. Each turbine and anemometer also has its own dedicated 12 strand fiber optic bundle for communication to the central control building via TCP/IP. As all data is synchronized in acquisition, transmitting the data via non-deterministic TCP/IP to the control building does not result in errors so long as the local time-stamps are matched up in the combined data storage in the control building. Currently, only 2 strands of each fiber bundle are used, this would allow for dramatic future expansion of the amount of data transferred. Additionally, in the future all turbines and anemometer towers could be connected into a single EtherCAT chain without any significant effort. The machines are not currently connected into a single EtherCAT chain because the entire chain would have to stop operating if any single element, such as a turbine, needed to be removed.

B. Scaled Wind Farm Technology Facility Model Updating

In recognizing the importance of detailed component models to overall system performance accuracy, SNL contracted ATA Engineering to experimentally characterize each main component and sub-assembly to determine mass properties and essential modal characteristics [14]. Traditional impact modal tests and naturally excited modal tests were also performed on each fully installed wind turbine giving an estimate of structural variability. The structural changes caused by a new generator modified the mass properties of the turbine. As these properties are fundamental to the system behavior they needed to be measured experimentally. The boundary condition for the entire system, the foundation, was also completely redesigned, and is again crucial to the system performance. The aeroelastic models used to predict system performance was updated in order to reflect the experimentally characterized components.

The tests performed on the components, sub-assemblies, and full turbines were:

- Mass properties and modal characteristics of 6 wind turbine blades
- Mass properties of the rotor hub
- Mass properties of the nacelle

- Free-free modal analysis of each tower
- Modal analysis of each tower mounted to the installed foundation
- Full turbine artificially excited modal analysis
- Naturally excited (wind) modal analysis of one turbine

(a) 

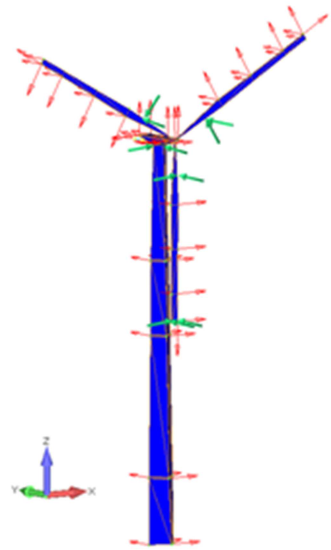
(b) 

Figure 5. Modal testing on full turbine system (a) and display model showing measurement locations (b).

Figure 5 shows an image taken during the full turbine artificially excited (impact) modal test, as well as the test display model (TDM) which was used for analysis of the results. Each arrow in the TDM represents an acquired acceleration measurement.

Initial models of each component were developed using available documents and design drawings when available from the original manufacturer. The averaged mass properties of the nacelles and hubs were needed for inputs into the aeroelastic and multi-body dynamic analysis codes for correct turbine response and performance predictions. These were estimated by ATA Engineering from a combination of load cell and vibration measurements, the results are shown in Table 3.

Table 3. Mass properties of V27 nacelle and hub

	Nacelle*	**Hub****
Mass (kg)	7007	477
CGx (m)	0.64	-0.08
CGy (m)	0.08	0.015
CGz (m)	.09	0.005
Ixx (kg*m^2)	2511	69.1
Iyy (kg*m^2)	10406	76.3
Izz (kg*m^2)	9589	86.2
*Nacelle origin defined on center of tower axis and top of yaw bearing		
**Hub origin defined at center on the rotor plane		

Note: Coordinate systems defined per standard as expressed in [15].

Several tests were conducted throughout the measurement campaign on each 13 meter turbine blade. A mass properties test and modal analysis test was conducted by ATA Engineering, and a static pull test on each blade was conducted by the National Renewable Energy Laboratory (NREL) as a certification criterion for receipt of the wind turbine blades from the supplier. The initial model of the turbine blades far under-predicted the mass and missed the CG location (585 kg, 4.77m) and was off on the static load cases. Details which were not expressly provided by the design documentation, or which were determined to be questionable within the blades were updated, such as fabric thickness, density of infused epoxy, exact material layup etc. were scaled within realistic realms in order to provide good correlation with all collected test data. Table 4 displays the resulting blade model properties in comparison with the average of all blade tests. The properties of this updated model were used to create the aeroelastic model to predict system performance.

Table 4. Blade testing and model results

	Mass (kg)	CG (m)	1st Flap (Hz)	1st Edge (Hz)	2nd Flap (Hz)
Model	641.9	4.31	4.82	10.09	12.56
Average Experimental	659.2	4.195	4.86	11.53	12.45
Percent Difference	-2.63%	2.74%	-0.8%	-12.5%	0.9%

The turbine towers are steel conical tubes with a length of 31 meters and weighing approximately 12000 kg. Each tower was tested in a free-free configuration by resting them on specially designed stands and inflating a set of airbags. The results of the free-free test were used to update the tower properties of the 3D finite element shell model. Results of the free-free calibration are shown in Table 5 and the updated tower properties are shown in Table 6. The effective density of the tower is slightly higher than expected (7850 kg/m^3 is standard for steel) due to the added mass effects throughout the tower, such as the ladder, cabling etc. that have not been included in the model.

Table 5. Free-Free tower calibration results.

	ANSYS, Hz	Tower 1, Hz	Tower 2, Hz	Experimental Avg., Hz	Difference
1st Bending	10.7	10.66	10.61	10.635	0.61%
1st Bending	10.7	10.88	10.69	10.785	-0.79%
2nd Bending	28.055	28.34	28.29	28.315	-0.92%
2nd Bending	28.055	29.1	28.8	28.95	-3.09%

Table 6. Updated tower properties.

Elastic modulus, GPa	193.94
Poisson ratio	0.3
Shear modulus	$\frac{E}{2(1+\upsilon)}$
Density, kg/m^3	8713

The foundation stiffness is an important parameter to the performance of the turbine which is difficult to measure directly. In order to quantify this stiffness, a modal test was performed with the tower installed on the foundation. A 2-dimensional beam model was created with the updated tower properties in order to represent the foundation as a translational and a rotational spring at the base of the tower. A translational and a rotational spring of 0.35 GN/m and 6.5 GN-m/theta, respectfully, were added to the already correlated free-free tower model. The order of magnitude of the springs was initially based upon design documentation and typical foundation stiffness for similar turbines and updated to minimize frequency difference and maximize the raw correlation of each mode.

The experimental frequencies of the first two fore-aft and side-side bending modes were averaged in order to provide a representative 2-D solution for comparative purposes, as there is only a single first and second bending mode (fore-aft and side-side are not distinguishable). The experimental mode shapes of the tower on foundation test were scaled to unit-modal-mass and used for comparison to the tower model with approximated foundation stiffness. The full-space 34 degree of freedom (DOF) model was reduced to 5 translational DOF that corresponded to measurement locations of the tower by the System Equivalent Reduction Expansion Process (SEREP) [16], which preserves the target mode shapes and frequencies exactly during the reduction process. For correlation, a Modal Assurance Criterion (MAC) and a Pseudo-Orthogonality Check (POC) [17] were performed on the experimental and reduced model DOF. The results of the correlation are shown in Table 7. For display purposes the experimental shapes were then expanded to full space using the SEREP method, shown in Figure 6.

Table 7 Tower on foundation experimental vs. model correlation.

Mode	Exp (Hz)	Model (Hz)	% Difference	MAC	POC
Mode 1	2.68	2.62	1.7	0.99	1.0
Mode 2	11.55	11.51	0.3	0.99	0.99

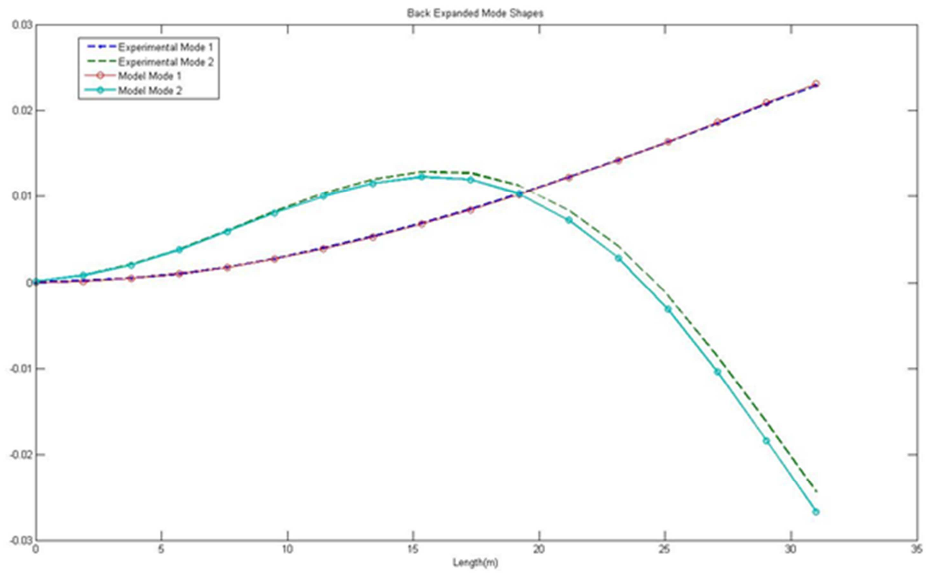


Figure 6. Expanded mode shapes of V27 tower installed on foundation.

The full turbine aeroelastic model was updated to reflect each of the test-correlated finite element models and mass property analyses. Table 8 shows the results of each modal test for each test turbine. The frequencies and modal responses correlate fairly well between the two tests, with frequency differences generally less than 5% which is well within expected test variation. The tests took place on different days with different wind conditions, and temperatures, which can add to test variation. The second turbine also had a reduced set of instrumentation due to test timing and project costs which can lead to lower mode shape correlation or MAC values.

Table 8: Full turbine modal test results

	SNL1		SNL2				
Mode	Frequency (Hz)	Damping (% Crit.)	Frequency (Hz)	Damping (% Crit.)	Diff (%)	MAC	Description
1	1.00	3.39	0.97	2.66	-3%	96	1st Tower Bending Edgewise
2	1.01	3.82	0.99	2.95	-2%	83	1st Tower Bending Flapwise
3	2.02	2.48	1.88	2.87	-7%	68	1st Blade Flapwise Bending - Asym
4	2.04	2.51	2.00	2.36	-2%	50	1st Blade Flapwise Bending - Asym
5	2.40	2.13	2.37	1.59	-1%	82	1st Blade Flapwise Bending - Sym
6	3.65	1.45					1st Blade Edgewise Bending - Asym
7	3.73	1.24	3.75	0.01	0%	32	1st Blade Edgewise Bending - Asym
8	5.33	1.35	5.05	1.96	-5%	76	2nd Blade Flapwise Bending - Asym
9	5.36	1.46	5.34	1.26	0%	68	2nd Blade Flapwise Bending - Asym
10	6.67	1.20	6.70	0.98	0%	88	2nd Blade Flapwise Bending - Sym
11	7.83	1.38	7.76	1.18	-1%	90	2nd Tower Bending Flapwise
12	7.97	1.19	7.99	1.52	0%	85	2nd Tower Bending Edgewise
13	8.43	1.32	8.34	0.80	-1%	89	1st Tower Torsion, 2nd Blade Edgewise Bending
14	9.67	1.65	9.99	1.64	3%	73	2nd Blade Edgewise Bending - Sym
15	11.15	1.19	11.12	1.29	0%	83	3rd Blade Flapwise Bending - Asym
16	12.52	3.64					3rd Blade Flapwise Bending - Asym
17	12.69	1.70	12.17	2.68	-4%	84	2nd Blade Edgewise Bending - Asym / 3rd Blade Flap - Asym
18	13.45	1.06	13.22	1.11	-2%	71	2nd Blade Edgewise Bending - Asym
19	13.66	1.08	13.82	1.98	1%	66	2nd Blade Edgewise Bending - Asym / 3rd Blade Flap -Sym
20	13.80	1.04					3rd Blade Flapwise Bending -Sym

IV. Linking Modeling Requirements with Experimental Capabilities

In order to understand the effect of turbine wakes that occur in commercial wind farms, the SWiFT Facility was built to replicate and measure relevant conditions. The combination of a consistent wind direction and the layout of the SWiFT turbines can be used to simulate many of the basic turbine to turbine interaction situations.

From the southeast, all three turbines operate with clean inflow and can provide a control production for the downwind SNL2 turbine, as shown in Figure 3. From the south, SNL1 directly wakes SNL2 at the spacing of six rotor diameters. From the southwest, the Vestas turbine wakes SNL2 at six rotor diameters. For an extreme scenario of wind coming down a row of turbines, winds directly out of the west (which often occurs during storm events in the spring) would result in a condition of the Vestas turbine waking SNL1 at three rotor diameters. Many of the wind directions between the south and west create partial wake shadow on the downwind turbine, which can cause rotor imbalances and damage to turbine components.

The intensity of the wind turbine wake is directly related to the coefficient of thrust (Ct) of the rotor. In partial power production (Region II of the variable speed control), the turbine operates at its optimum tip-speed-ratio (TSR) and ideal induction, producing the maximum Ct. After the turbine reaches peak power output (Region III), the blades feather lowering the induction and the Ct. Therefore the influence of the wake should be at a maximum in wind speeds between 5 m/s and 13 m/s.

Wind turbine wakes transition from an organized near wake with a strong tip vortex, to a disorganized highly turbulent structure. This transition happens in the range of three rotor diameters downwind, but is influenced by the free stream turbulence and atmospheric stability. The progression of these wakes affects the downwind turbines. The two factors that drive power performance losses and increased component damages are the increased turbulence and the mean deficit from the free stream wind speed.

There are three elements of measurement needed to quantify the turbine-to-turbine interactions. The first element is a clear distributed measurement of the inflow as discussed previously. The next element is the instantaneous performance of the wind turbine operating in the clean inflow to characterize its thrust. The final element is recording the operation of the waked turbine to quantify underperformance and loading that will increase fatigue damage.

To understand the inflow to the SWiFT turbines, the instrumentation on the met towers placed 2.5 rotor diameters in front of the SNL1 and Vestas will be used. Using the combination of cups and sonic anemometers, the velocity and shear across the rotor disc can be calculated to establish the free stream wind. In addition, the spectrum of turbulence can be obtained at five sonic anemometer heights to categorize wake events. For additional characterization, NWI's 200 m met tower and SODAR on site will be used to provide the atmospheric stability during wake events. For large weather events in the region, data can be obtained from NWI's West Texas Mesonet to follow and predict patterns before they reach the site or for calibration of large-scale weather models. The combination of atmospheric and local meteorology measurements gives high confidence that the events that take place on site at SWiFT will be well understood.

The next step is to understand the rotor producing the wake. Determining the Ct of the rotor is the critical measurement for non-dimensionally categorizing the effect of the wake on the free stream. The instantaneous power output and the coefficient of power (Cp) of the rotor will be used to make the correlation to Ct. Approximations can be made using the momentum equations:

$$T = \rho \times A_1 \times V_1 \times (V_0 - V_2) \tag{1}$$

$$P = T \times V_1 \tag{2}$$

$$P = \rho \times A_0 \times V_0^2 \times (1 - a) \times (V_0 - V_2) \tag{3}$$

where ρ is air density, A_0 is swept area of the momentum upwind momentum tube, A_1 is the swept area of the rotor, V_0 is free stream velocity, V_1 is the velocity at rotor disk, V_2 is velocity in the far wake, and a is the axial induction factor.

Data will also be recorded on the tower top movement of the turbine using an inertial measurement unit. Using this information with the results from the modal tests will give another method to determine time averaged thrusts during wake events. To understand the directionality of the wake and the effect of yaw error, an absolute encoder has been added to the yaw system giving a precise, calibrated yaw orientation. This is a critical measurement that is either not available or unreliable in commercial SCADA data.

Finally the effect of the upwind turbine wake on the downwind turbine will be measured. Most often this will be the SNL2 turbine, with the variety of wake scenarios described above. On the downwind rotor, the power produced will be tracked and compared to the upwind rotor to understand the gross effect of the wake on power production. The results will be categorized by the severity of wake shadow, wind shear, atmospheric stability, and free stream turbulence intensity.

Data will be recorded to identify damage-causing loads on the waked turbine. The low speed shaft is instrumented with an absolute encoder to provide the azimuth position of each blade. Additionally, optical strain gauges are installed to measure edgewise and flapwise blade root bending on all three blades. Binning these measurements by azimuth will identify partial wake shadow situations. Comparisons can also be made in the instantaneous bending of all thee blades to determine rotor imbalance. While wind shear can cause these imbalances with clean inflow, it is expected that the effects will be more extreme when operating in the wake of another turbine. These loads can cause excessive fatigue in components like, pitch systems, main bearings, gearboxes, and yaw systems.

Collecting all of this well characterized experimental data alone is not enough for the industry to use to make great leaps in turbine park performance. Thousands of load cases are done in the design of a wind turbine and these cannot all be captured at any field site. Some of these events are once in 50 year events for extreme load cases. Therefore, the knowledge from these experiments must be used to create better tools for designing wind farms. This includes single turbines designed to function as a park, improvements in turbine placement pre-construction, as well as making modifications to existing parks to extract extra energy or reduce the O&M costs. There are two primary tools in development to aid in all of these areas: large scale Large Eddy Simulation (LES) and the Dynamic Wake Meandering (DWM) model [18].

The LES model is under development at NREL [19]. The purpose of this model is account for the atmospheric effects that influence the progression and decay of a wind turbine wake. In order to model the both the atmospheric scales and the scales of the blade, the turbine rotor is not resolved with LES. Instead the influence of the blade is included as source and imbedded in the flow. Because of the computation time involved, the current use for this tool would be for investigating specific scenarios and conducting forensic analysis. The SWiFT facility has critical elements for creating correlations with simulations from this model. The combination of scales of measurements will allow accurate recreation of events at the site using this model.

The limitations in computation time prevent the LES model from being a design tool when hundreds or thousands of simulations need to be run. The model being created for use in these cases is the DWM model. This model can solve in seconds, but will require some tuning to match effects in the field. The data from SWiFT can be used to validate this model for a variety of conditions giving designers confidence in the results of the simulations.

These models can provide immense value to the industry in the future. But without validation from well executed field experiments, the effectiveness will be limited. Using the above described tools, new technologies can be developed and tested at the facility to verify that the improvements exist in the field, as is done in simulation.

V. Turbine-Turbine Interaction Experiments

The following section describes work planned that will be performed. The original intent of this paper was to provide some preliminary data from the SWiFT Facility, but due to unexpected issues at the facility in Fall 2013 that was not possible.

A. Performance Effects Due to Turbine-Turbine Interaction

The layout of the SWiFT facility and the site's custom-built time-synchronized data acquisition capability provide a unique opportunity to investigate how operation of the first-row turbines affects the performance of the second-row turbine. Although other studies have shown performance penalties on turbines behind the first row, the results are typically obtained from analysis of SCADA data which is limited in resolution to 1-minute or 10-minute averages. The data captured at SWiFT will allow an in-depth look at the impacts down to fractions of a second resolution.

Analysis of the performance effects will begin at the high level results which can be observed in SCADA-type data. This will include the power production of the first-row turbines compared to that of the second-row turbine. Statistical distributions of each turbine signal will also be computed and subsequent analysis of the variation between turbines in signal mean and spread should reveal overall trends in the turbine-turbine interaction problem.

Diving down into a greater level of detail, the performance effects will be investigated with attention given to the "waked state" of the second-row turbine, in other words, whether or not either wake from the front row of turbines was impinging upon the rear turbine. The meandering behavior of the rotor wakes will require specialized analysis of sensor signals to identify periods of time when a waked condition existed. Verification of the waked state analysis will be attempted with LIDAR, SODAR, or the wake imaging measurement system described below.

Having identified the breakdown in time of waked and non-waked conditions, statistical analysis will be conducted on each condition to directly determine the effects of operating under a waked condition. Comparing statistics of the first and second row turbines should provide a double-check of the conclusions reached regarding waked operation and may also reveal that the downwind turbine experienced additional performance effects whether or not it was directly waked.

B. Discussion and Future Experimentation

1. Wake Imaging Measurement System

There is a growing need for a new experimental measurement tool that is capable of investigating the relevant physics of wind turbine wakes and validating the computational methods used to model those flows. Current flow measurement tools such as Particle Image Velocimetry (PIV) or scanning LiDAR are either impractical or insufficient to capture wind turbine flow data in the field at the required temporal and spatial scales. Sandia National Laboratories is currently developing a flow measurement system based upon a laser velocimetry technique called Doppler Global Velocimetry (DGV). While DGV has been successfully implemented many times in subsonic and supersonic wind tunnels including the NASA Ames Research Center 40x80 foot national full-scale aerodynamic complex (NFAC), few if any experiments have been attempted in the field. The prototype system is currently under development to evaluate the system capabilities and define the specifications of the eventual field-deployable system to be implemented at the SWiFT facility. Though the final capabilities of the system have yet to be determined, the goal is to obtain three-component velocity measurements simultaneously across a large volume at high spatial resolution. This method is not intended to match the precision of current point measurement methods, but rather to augment existing tools through the collection of instantaneous velocity images of flow structures, a critical gap in current instrumentation. With this fundamentally different approach to flow measurements, the system has the potential to contribute significantly towards a better understanding of the near-wake rotor flow physics and drive improvements in current computational wake models.

2. Advanced Rotor Projects

The SWiFT facility currently features 1980's era rotor technology. While the aerodynamic and structural technologies used in the OEM rotors of the V27 enabled a cutting edge product in their own time, today's modern turbines (1.5-3MW ratings with rotor diameters of 70-120m) take advantage of an additional 20+ years of wind energy rotor technology research. Today's modern rotors are designed to a new level of optimal aerodynamic and structural efficiency. A new blade set for the SWiFT turbines is being designed by Sandia and will replace the OEM blades with blades that, as much as possible, are aeroelastically similar to typical full-scale, megawatt turbines used by the industry today. In particular, the DOE A2e Program has set goals to understand the complex flow issues associated with modern rotors and wind farms so a new rotor design will aim to reproduce relevant characteristics of a full scale rotor design such that aerodynamic loads and wakes between SWiFT scale and megawatt scale are as similar as possible. More detailed discussion of this rotor design can be found in the 2014 AIAA paper by Resor and Maniaci [20].

New blades are expected to represent a new baseline for research scale field testing of rotor technology; they are designated the National Rotor Testbed (NRT). Modern rotors come with their own challenges: acoustics, controls, sensing, aerodynamics and structural dynamics. Beyond the National Rotor Testbed, there will be additional rotor design iterations that are focused on studying these important including

- structural design to enable passive load control,
- active flow control (SMART rotor) to enable load control,
- quiet blade technology to enable larger and faster rotors and
- use of flexible, aeroelastically very active, blades to expand the design space of large rotors.

VI. Summary

The DOE/SNL SWiFT Facility is a state of the art facility built to perform research and development in turbine-turbine interaction, advanced rotors and fundamental studies in aeroelasticity, aeroacoustics, and aerodynamics. In this paper a review of previous work in scaled and full-scale testing was provided. A detailed overview of the design and installation of the facility was presented. Finally, a discussion covered a variety of future experiment planning topics and projects that will be performed at the facility.

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References

1. Hand, M. M., Simms, D. A., Fingersh, L. J., Jager, D. W., and Cotrell, J. R. "Unsteady Aerodynamics Experiment Phase V: Test Configuration and Available Data Campaigns." National Renewable Energy Lab., Golden, CO, 2001.
2. Hand, M. M., Simms, D. A., Fingersh, L. J., Jager, D. W., Cotrell, J. R., Schreck, S., and Larwood, S. M. "Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations and Available Data Campaigns." National Renewable Energy Laboratory, Golden, CO, 2001.
3. Castaignet, D., Barlas, T., Buhl, T., Poulsen, N. K., Wedel-Heinen, J. J., Olesen, N. A., and Kim, T. "Full-scale test of trailing edge flaps on a Vestas V27 wind turbine: active load reduction and system identification.," *WIND ENERGY*, 2013.

doi: 10.1002/we

4. Angelou, N., Mann, J., Courtney, M., and Sjöholm, M. "Doppler lidar mounted on a wind turbine nacelle – UPWIND deliverable D6.7.1.," *Risø National Laboratory* Vol. Risø-R-1757, 2010.
5. Bingöl, F., Mann, J., and Larson, G. C. "Laser Measurements of Wake Dynamics.," *Risø National Laboratory*, 2007.
6. Berry, D. S., and Ashwill, T. D. "CX-100 Manufacturing Final Project Report." Sandia National Laboratories, Sandia National Laboratories, 2007.
7. Berry, D. S., and Ashwill, T. D. "Design of 9-Meter Carbon-Fiberglass Prototype Blades: CX-100 and TX-100." Sandia National Laboratories, 2007.
8. Berry, D. S., and Ashwill, T. D. "TX-100 Manufacturing Final Project Report." Sandia National Laboratories, 2007.

9. Jonathan, B., Matthew, B., and Brian, R. "Field Test Results from the Sandia SMART Rotor," *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*. American Institute of Aeronautics and Astronautics, 2013.
10. Guntur, S., Bak, C., and Sørensen, N. N. "Analysis of 3D stall models for wind turbine blades using data from the Mexico experiment," *13th International Conference on Wind Engineering*, 2011.
11. Schepers, J. G., Boorsma, K., Cho, T., Gomez, S., Schaffarczyk, P., Jeromin, A., Shen, W. Z., Lutz, T., Meister, K., Stoevesandt, B., Schreck, S., Micallef, D., Pereira, R., Sant, T., Madsen, H. A., and Sørensen, N. "Final report of IEA Task 29, Mexnext (Phase 1): Analysis of Mexico wind tunnel measurements." ECN, 2012.
12. Campagnolo, F. "WIND TUNNEL TESTING OF SCALED WIND TURBINE MODELS: AERODYNAMICS AND BEYOND," *DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI*. Vol. PhD., POLITECNICO DI MILANO, 2013.
13. Barone, M., and White, J. "DOE/SNL-TTU Scaled Wind Farm Technology Facility: Research Opportunities for Study of Turbine-Turbine Interaction." Sandia National Laboratories, 2011.
14. LeBlanc, B., Marinone, T., and Cloutier, D. "Overview of the Dynamic Characterization at the SWiFT Wind Facility," *Proceedings of 32nd International Modal Analysis Conference*. Orlando, FL, 2014.
15. Jonkman, J. "NWTC Design Codes FAST." v7.01a ed., 2012.
16. O'Callahan, J., Avitabile, P., and Riemer, R. "System Equivalent Reduction Expansion Process (SEREP)," *Proceedings of the 7th International Modal Analysis Conference*. Las Vegas, NV, 1989.
17. Allemang, R., and Brown, D. "A Correlation Coefficient for Modal Vector Analysis," *Proceedings of the 1st International Modal Analysis Conference*. Orlando, FL, 1982.
18. Gunner C. Larsen, H. A. M., Ferhat, Bingöl, J. M., Søren Ott, Jens N. Sørensen,, Valery Okulov, N. T., Morten Nielsen,, Kenneth Thomsen, T. J. L., and Robert, and Mikkelsen, R. "Dynamic wake meandering modeling." Risø National Laboratory, Roskilde, Denmark, 2007.
19. Churchfield, M. J., Lee, S., Michalakes, J., and Moriarty, P. J. "A numerical study of the effects of atmospheric and wake turbulence on wind turbine dynamics," *Journal of Turbulence* Vol. 13, No. 14, 2012, pp. 1-32.
doi: Doi 10.1080/14685248.2012.668191
20. Resor, B. R., and Maniaci, D. C. "Definition of the National Rotor Testbed: An Aeroelastically Relevant Research-Scale Wind Turbine Rotor," *AIAA SciTech: 32nd ASME Wind Energy Symposium*. National Harbor, MD, 2013.